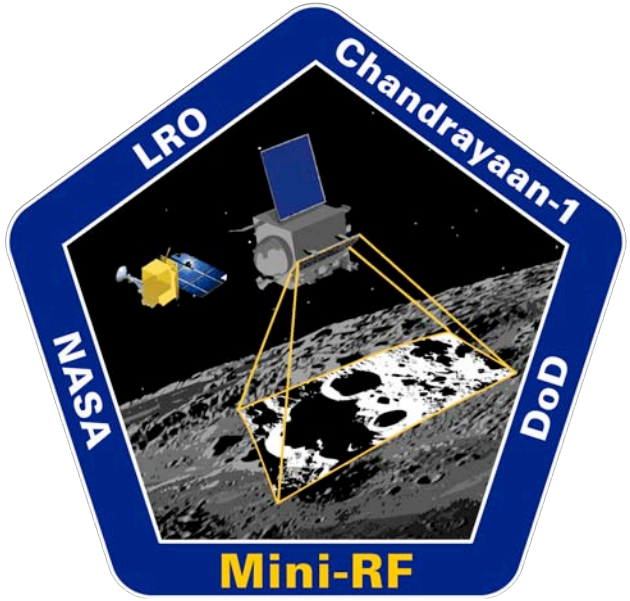
Mini-SAR

Results from Calibration, Mapping, and Analysis



P. D. Spudis, Lunar and Planetary Institute, Houston TX
D.B.J. Bussey, Applied Physics Laboratory, Laurel MD
S. Baloga, Proxemy Research Inc.
B. Butler, National Radio Astronomy Observatory, Socorro NM
L. Carter, National Air and Space Museum, Washington DC
M. Chakraborty, Space Applications Centre, ISRO, Ahmedabad India
J. Gillis-Davis, University of Hawaii, Honolulu HI
J. Goswami, Physical Research Laboratory, Ahmedabad India
E. Heggy, Jet Propulsion Laboratory, Pasadena CA
R. Kirk, U. S. Geological Survey, Flagstaff AZ
C. Neish, Applied Physics Laboratory, Laurel MD
S. Nozette, Lunar and Planetary Institute, Houston TX
M. Robinson, Arizona State University, Tempe AZ
R. K. Raney, Applied Physics Laboratory, Laurel MD
T. Thompson, Jet Propulsion Laboratory, Pasadena CA
B. Thomson, Applied Physics Laboratory, Laurel MD
E. Ustinov, Jet Propulsion Laboratory, Pasadena CA

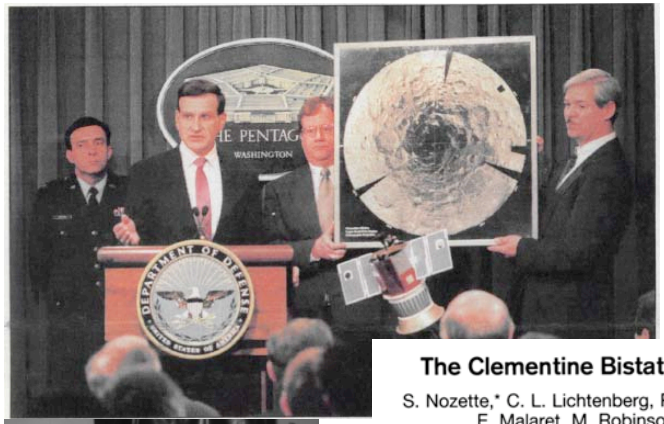
NLSI Lunar Science Forum

21 July, 2010

The search for lunar ice

"To be uncertain is uncomfortable but to be certain is ridiculous." – Goethe

- Radar has been used since 1960's to map the lunar surface
- Backscattering properties are different for normal Moon and water ice
- Long recognized that polar areas are dark and cold (Watson, Murray and Brown, 1961)
- Discovery of ice at poles of Mercury in 1992 spurred renewed interest in lunar poles
- Unfavorable viewing geometry complicated the interpretation of results
- Thus, 20 years of controversy



The Clementine Bistatic Radar Experiment

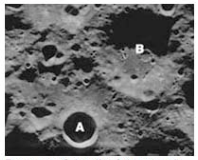
S. Nozette,* C. L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson, E. M. Shoemaker

During the Clementine 1 mission, a bistatic radar experiment measured the magnitude and polarization of the radar echo versus bistatic angle, β, for selected lunar areas. Observations of the lunar south pole yield a same-sense polarization enhancement around β = 0. Analysis shows that the observed enhancement is localized to the permanently shadowed regions of the lunar south pole. Radar observations of periodically solar-illuminated lunar surfaces, including the north pole, yielded no such enhancement. A probable explanation for these differences is the presence of low-loss volume scatterers, such as water ice, in the permanently shadowed region at the south pole.

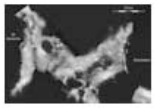
Ice Store At Moon's South Pole Is A Myth

by Staff Writers
Paris (AFP) Oct 18, 2006

Hopes that the Moon's South Pole has a vast hoard of ice that could be used to establish a lunar colony are sadly unfounded, a new study says. In 1994, radar echoes sent back in an experiment involving a US orbiter called Clementine appeared to show that a treasure trove of frozen water lay below the dust in craters near the lunar South Pole that were permanently shaded from the Sun.



Because of the tilt of the moon's orbital plane relative to the Earth's equatorial plane, the Earth can rise much higher above the



Water on the Moon? Scientists Await Definitive Answer

By Rick Callahan
Associated Press
posted: 01:00 pm ET
12 November 2003

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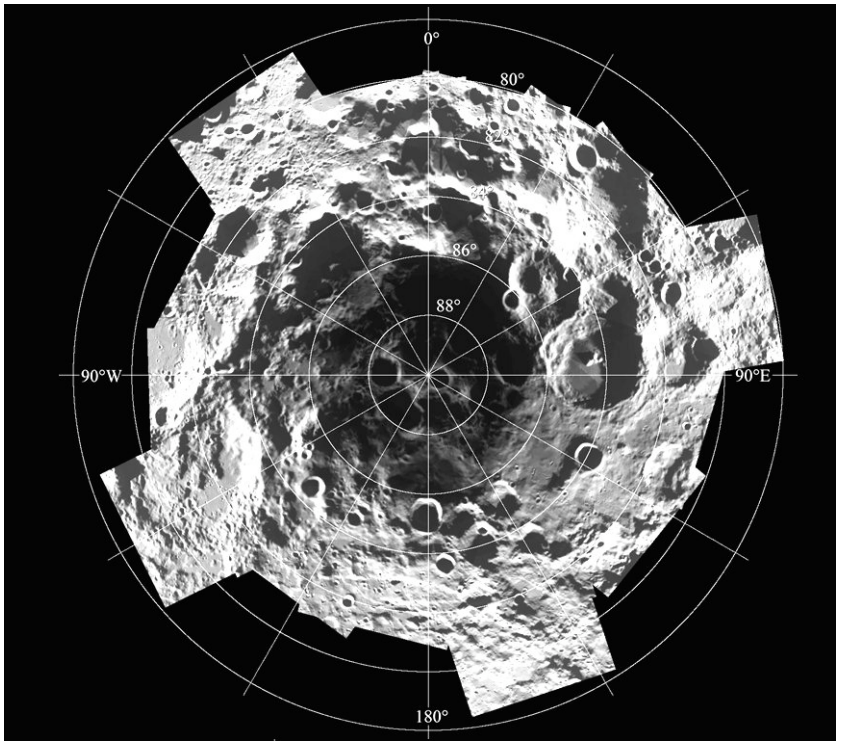
Mini-SAR Experiment Objectives

- Map the deposits of both poles of the Moon (> 80° lat.) at optimum viewing angles (~40°) to characterize permanently dark areas and definitively determine their RF backscattering properties using both SAR and scatterometry
- Complete the global map of the Moon by mapping dark regions in lunar polar areas
- Characterize the physical nature of the polar regolith and surface
- SAR mapping of other targets of opportunity as possible



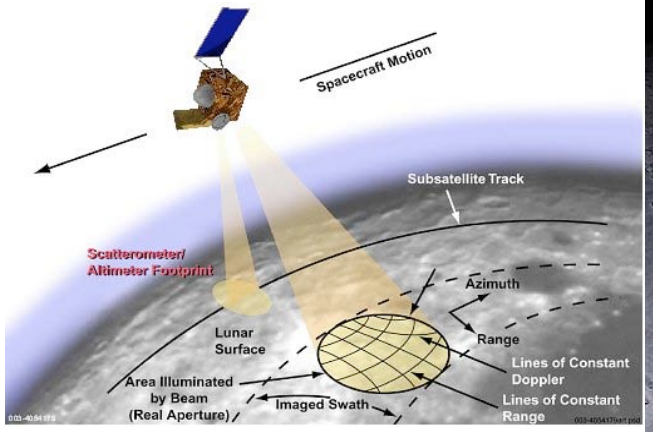
Moon South Pole
Clementine 750 nm base map

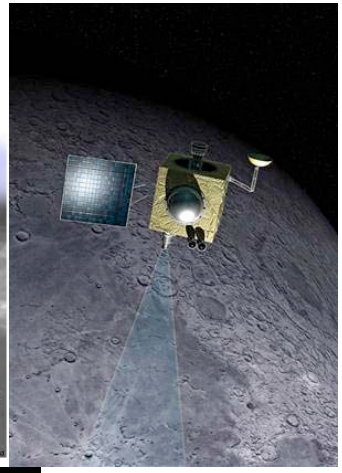
Mini-SAR

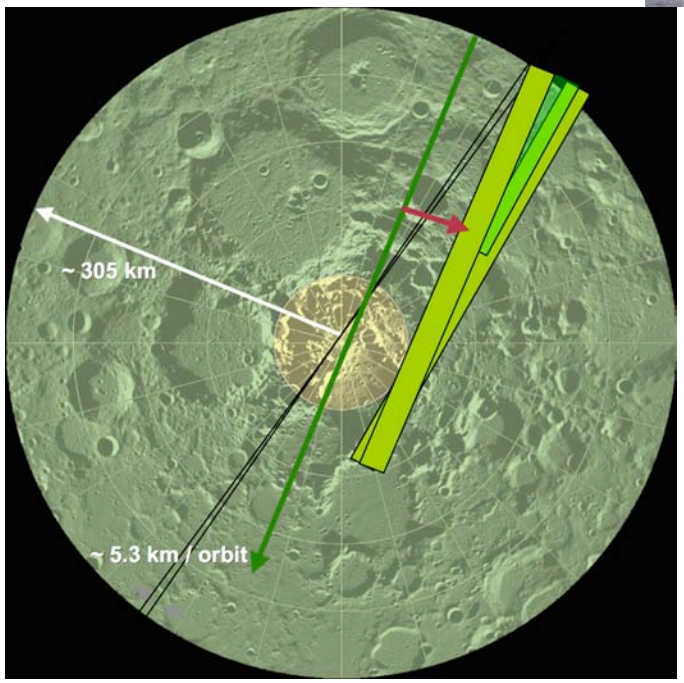
Imaging Radar on the Chandrayaan-1

- Mini-SAR is an S-band (13 cm) imaging radar with hybrid polarity architecture
- Map both polar regions at 75 m/pixel
- Transmit LCP, receive ***H*** and ***V*** linear, coherently
- Use Stokes parameters and derived "daughter" products to describe backscattered field
- Map locations and extent of anomalous radar reflectivity
- See polar dark areas (not visible from Earth)
- Cross-correlate with other data sets (topography, thermal, neutron)

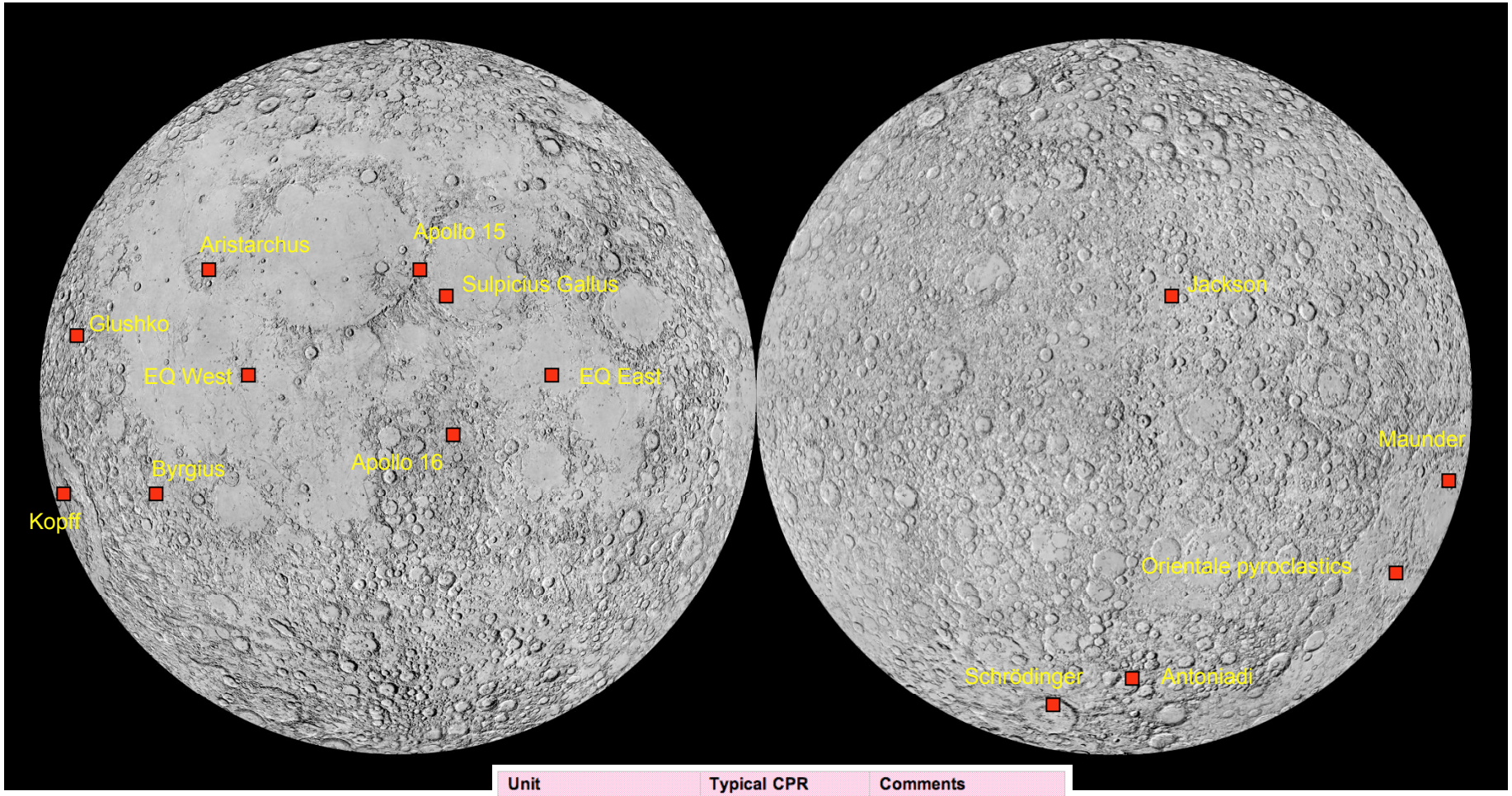
- LRO version (Mini-RF) has two bands (λ=13 and 5 cm), high-resolution zoom mode (15 m/pixel)





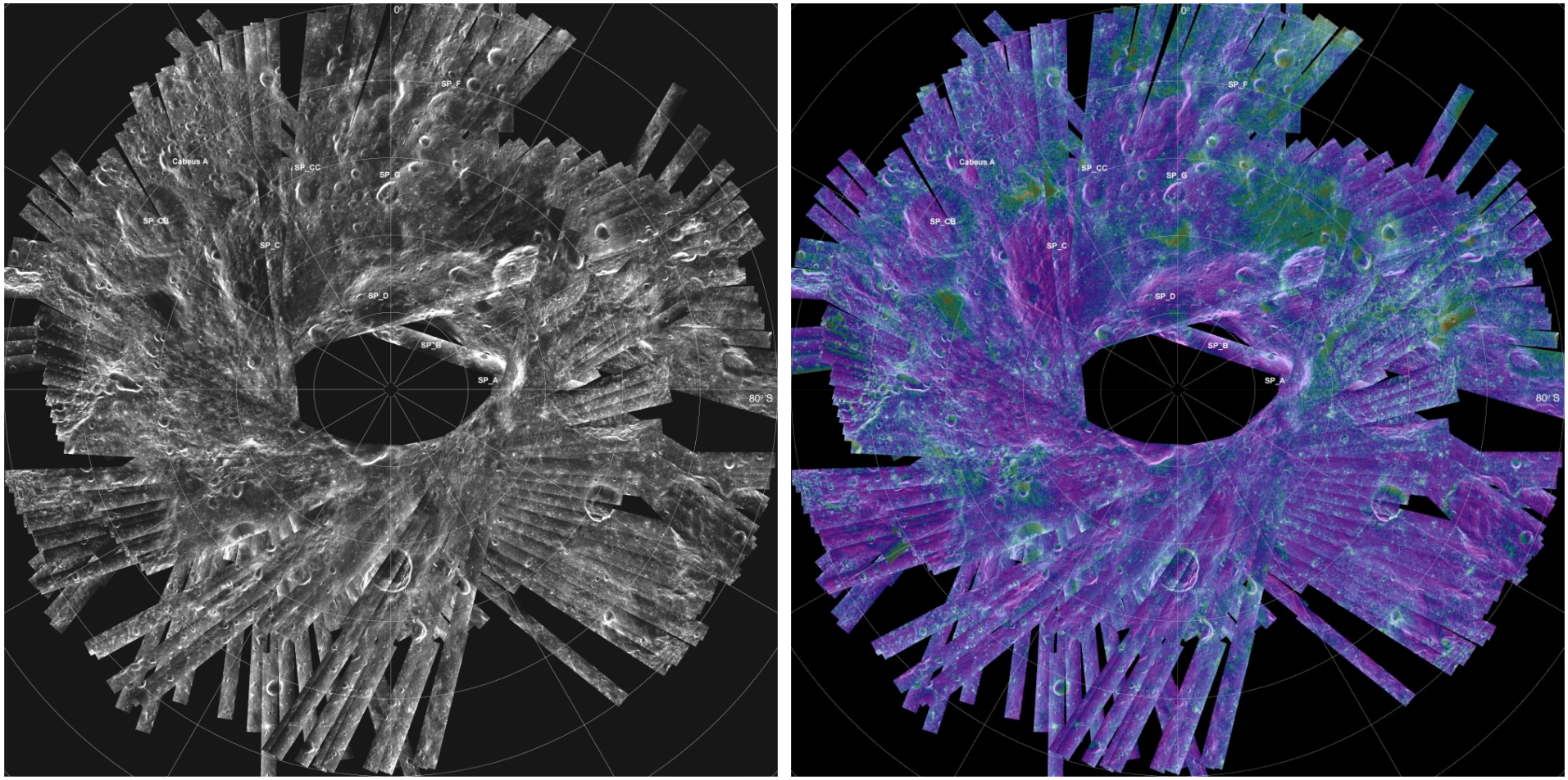


MSR non-polar targets

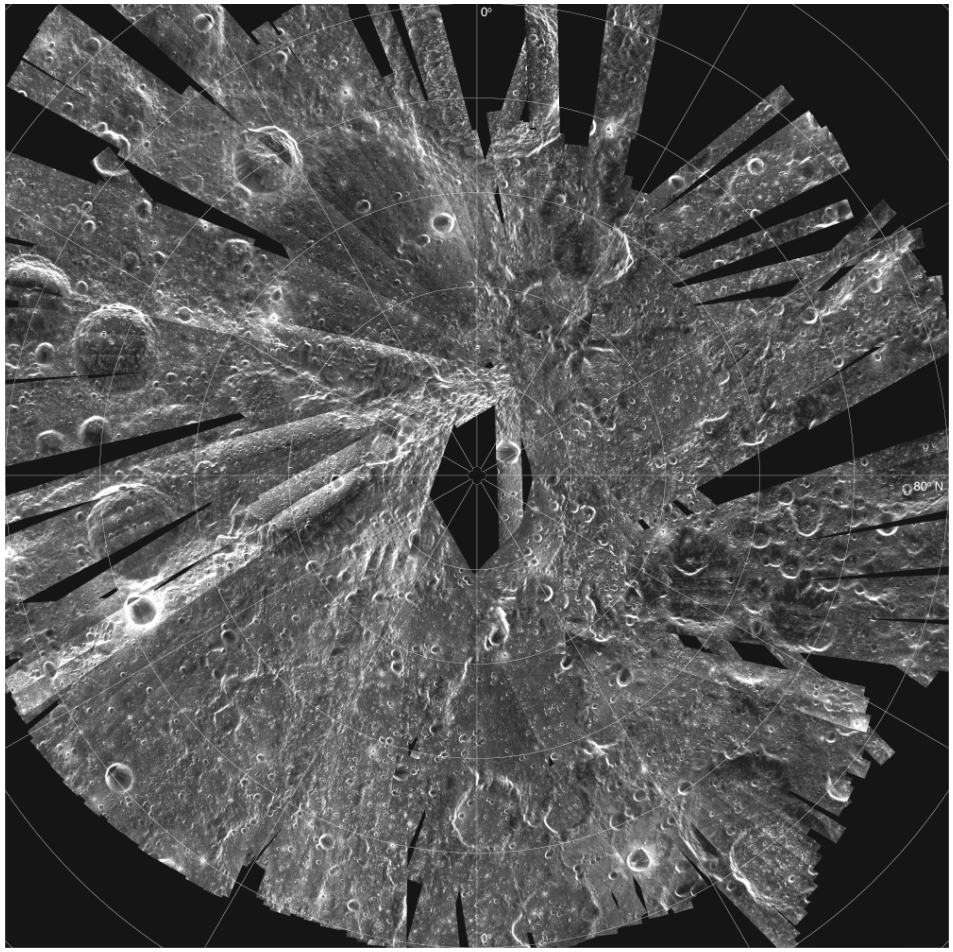


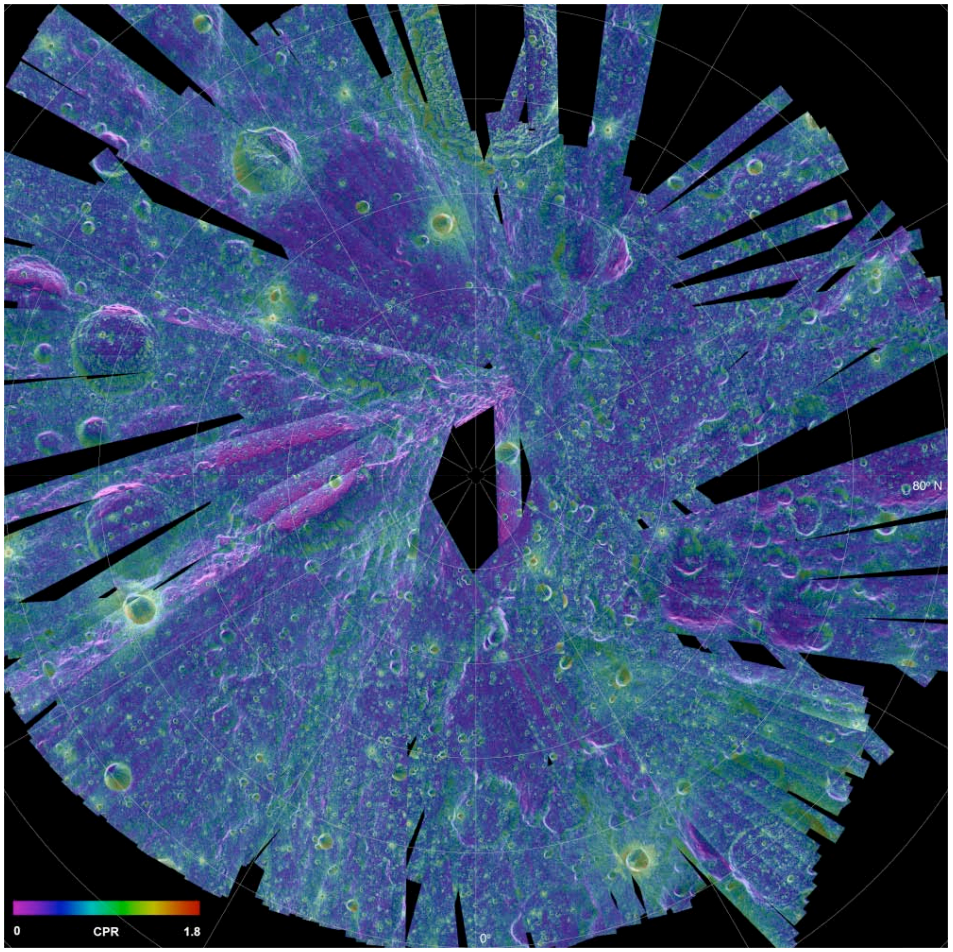
Unit	Typical CPR	Comments
Aristarchus (Copernican-age crater ejecta)	0.469 ± 0.149	Large fresh crater
Aratus (Copernican)	0.743 ± 0.239	Small fresh crater
Apollo 16 Cayley Fm.	0.311 ± 0.084	Highland plains
Apennine massif	0.713 ± 0.244	Mt. Hadley
Apennine intermontane	0.338 ± 0.128	Apennine backslope
"Young" maria	0.321 ± 0.113	West of Lansberg
Sulpicius Gallus Fm. dark mantle deposits	0.179 ± 0.055	Near vent

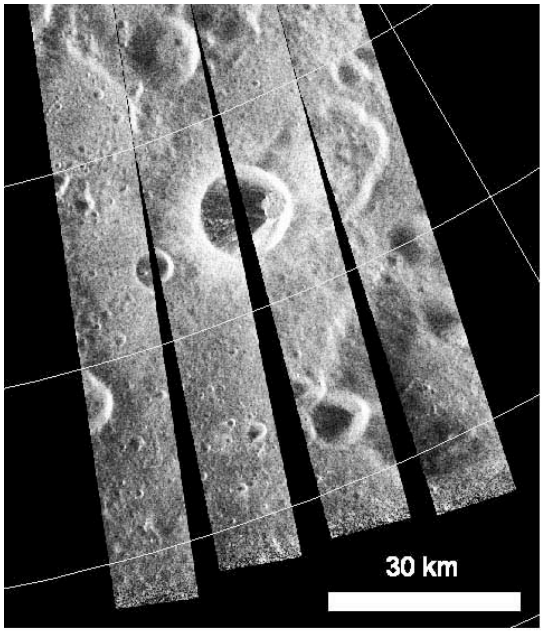
South Polar Mosaic

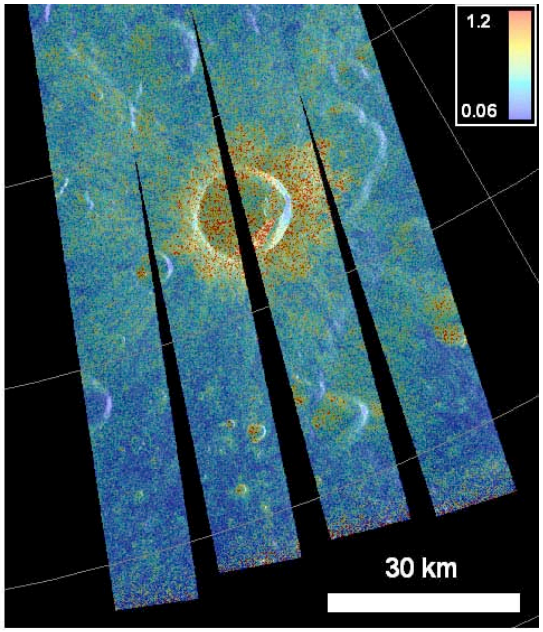


North Polar Mosaic





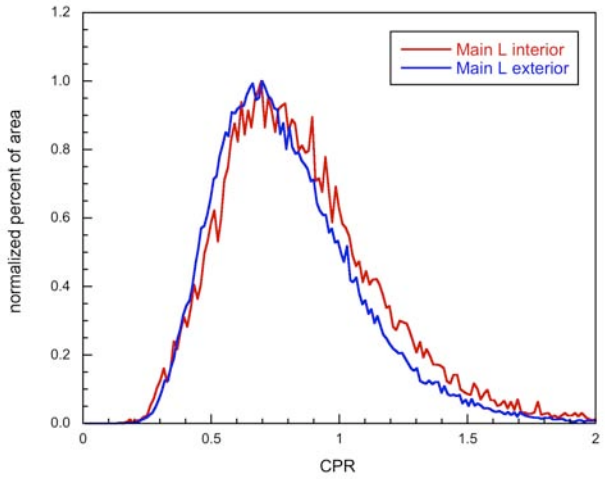




OS SAR image

Main L
14 km diameter
81.4° N, 22° E

CPR image



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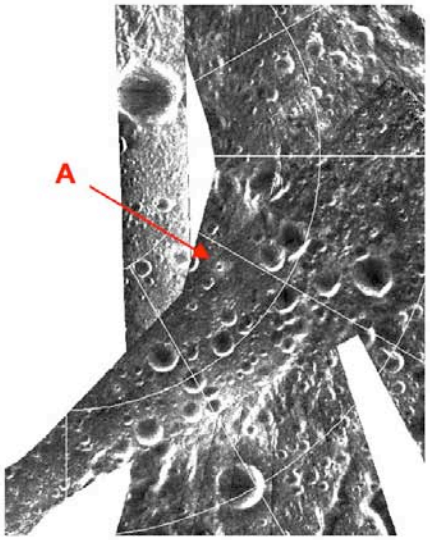
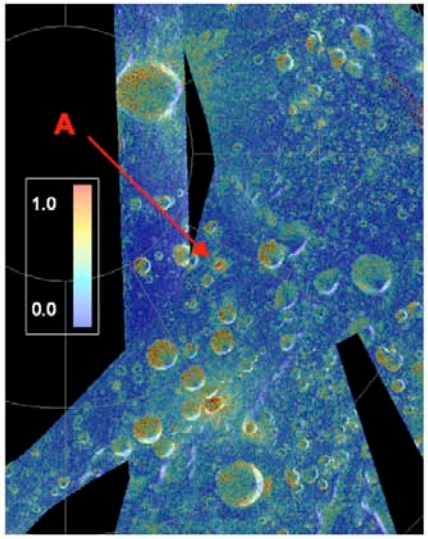
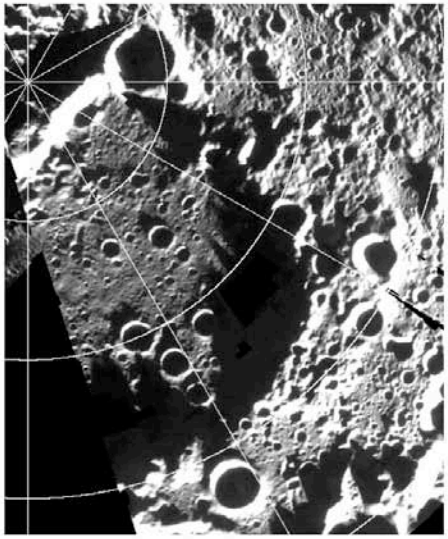




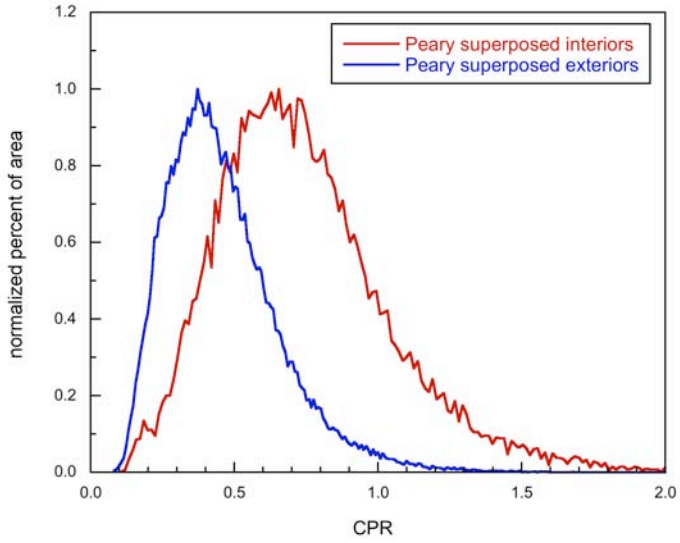


OS SAR mosaic

CPR mosaic

Clementine hires mosaic

Floor of Peary
73 km diameter
88.6° N, 33° E



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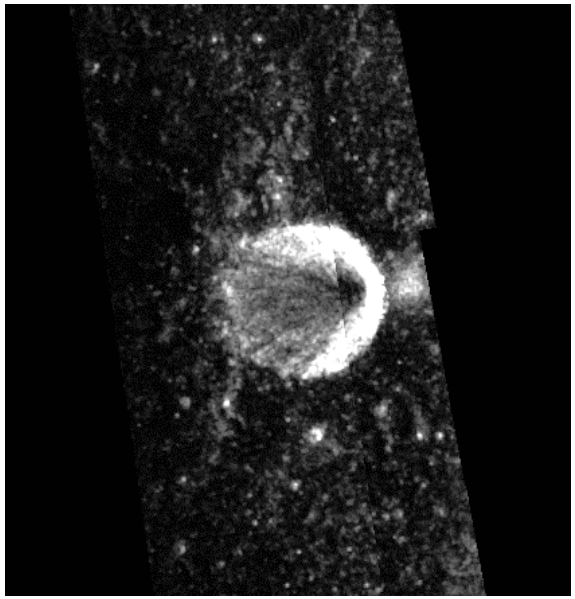
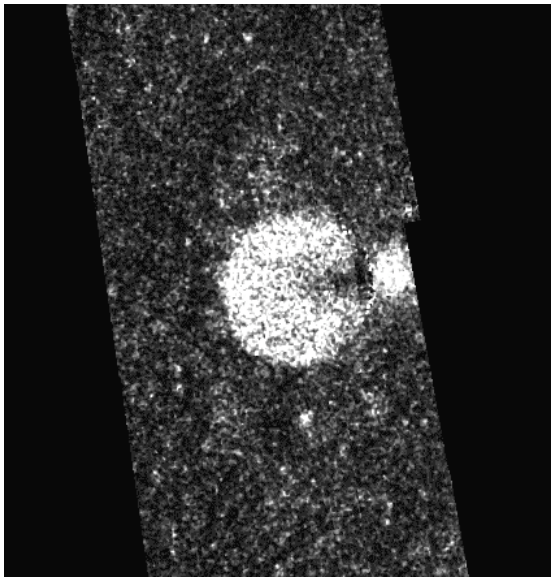
Anomalous polar crater

Rozhdestvensky N, 9 km diameter, 84.3 N, 157 W

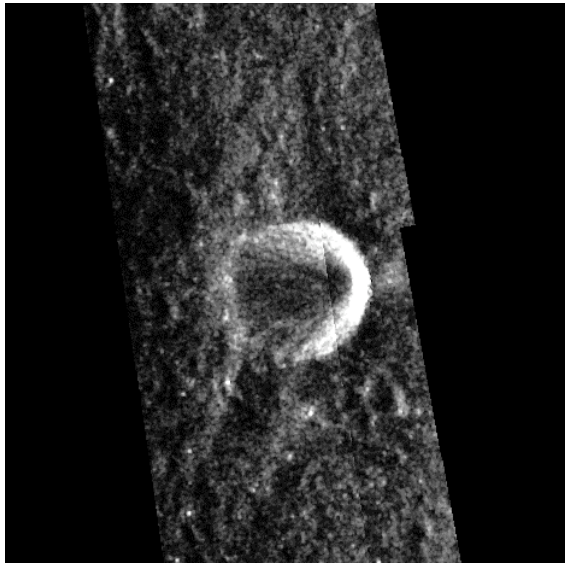
SC

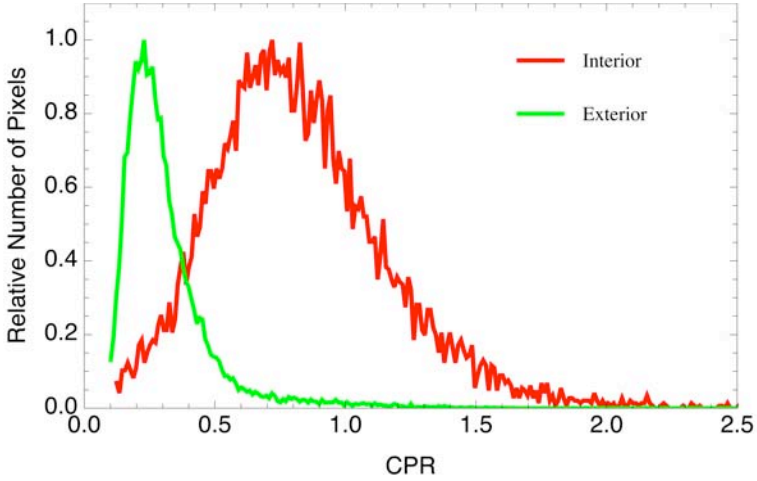




CPR

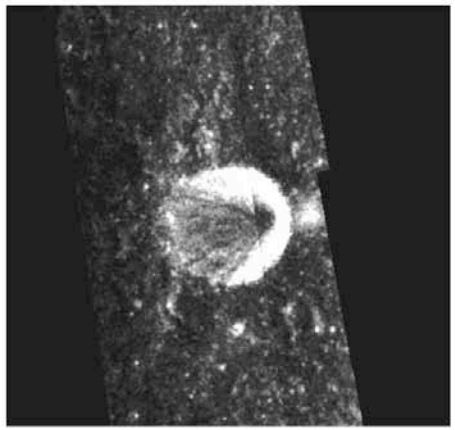
OC

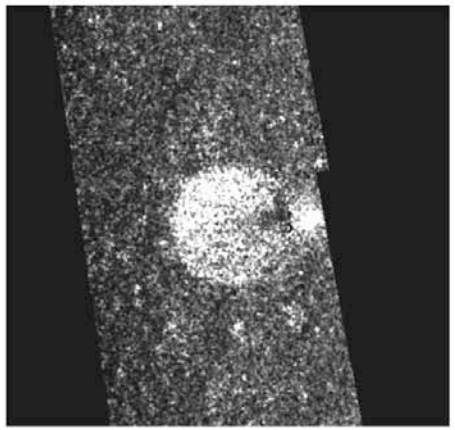




Rozhdestvensky N

SC

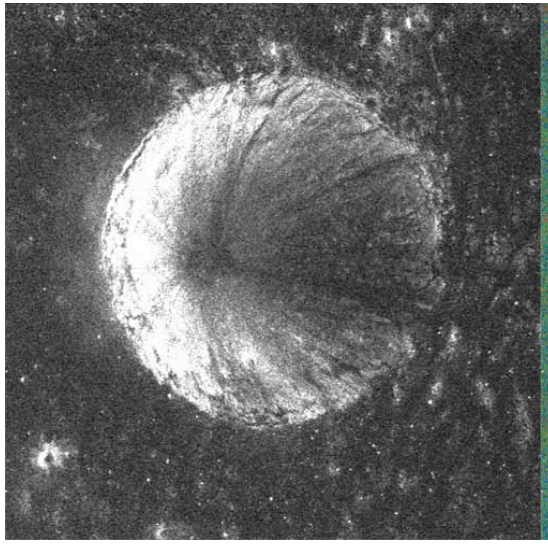


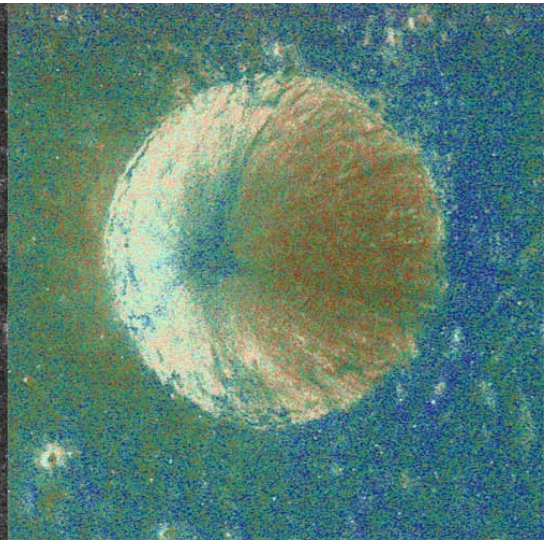


CPR

Illumination direction

SC

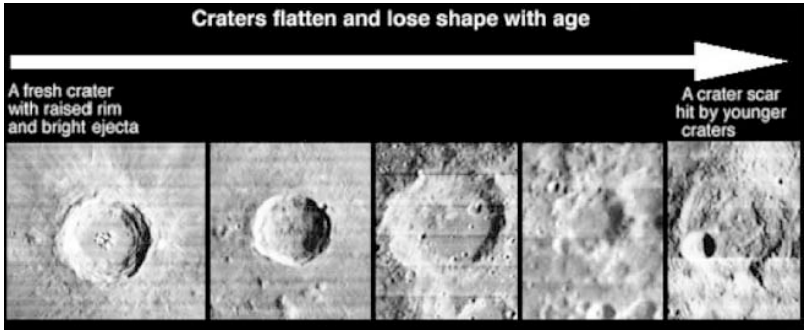


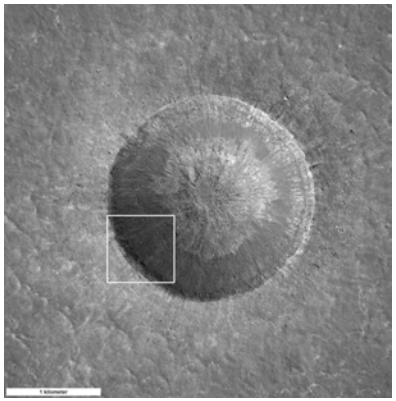


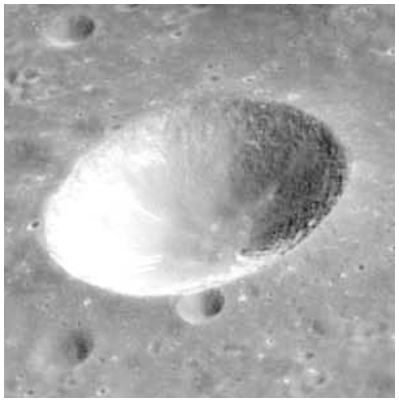
CPR

Geological evidence

- Anomalous craters have high CPR inside their rims, but not outside
- Fresh craters have high CPR inside and outside their rims
- As craters age and erode, this surface roughness is lost (rocks buried, eroded, covered by fine material)
- Degradation occurs both inside and outside of the crater rim
- Thus, the high CPR confined inside rims of anomalous craters is probably ***not*** caused by surface roughness







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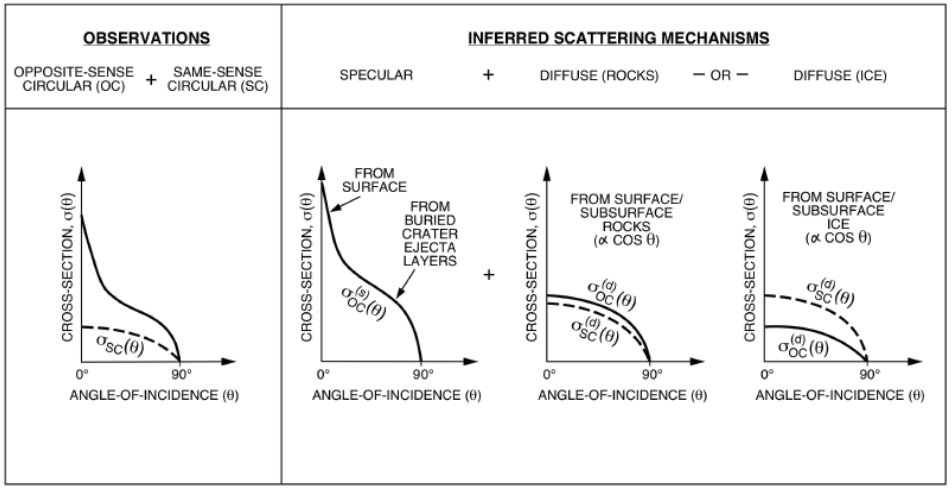
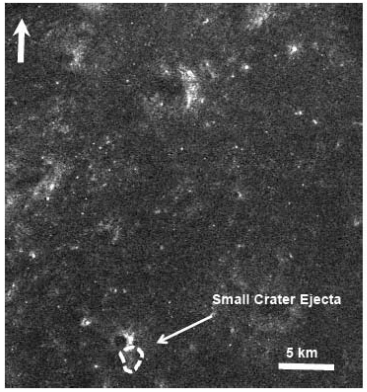
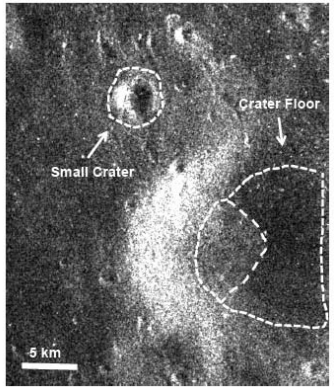
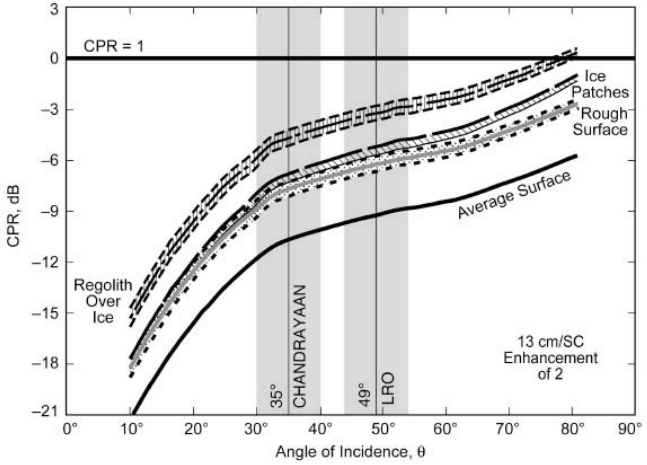
Modeling scattering from ice and regolith









Site	Small Mid-Latitude Crater Ejecta	Small Polar Crater (88-N)	Mid-Size Polar Crater Floor (88-N)	Mid-Size Polar Crater Bright Debris (88-N)
Alpha, SC Enhancement	1.66	1.38	1.75	1.72
Gamma, OC Enhancement	1.00	0.74	1.14	1.16
CPR-obs = (Alpha*CPR_avg)/Gamma	0.23	0.26	0.21	0.21
CPR Rough Surface Model	***0.24***	0.21	***0.25***	***0.25***
CPR Ice Patches Model	0.27	***0.23***	0.29	0.28
CPR Thin Regolith over Ice	0.42	***0.31***	0.45	0.44
	Matches Rough Surface	Matches Ice Patches and Thin Regolith over Ice	Matches Rough Surface	Matches Rough Surface

Separates for Thin Regolith over Ice from Rough Surface

No Separation for Ice Patches from Rough Surfaces

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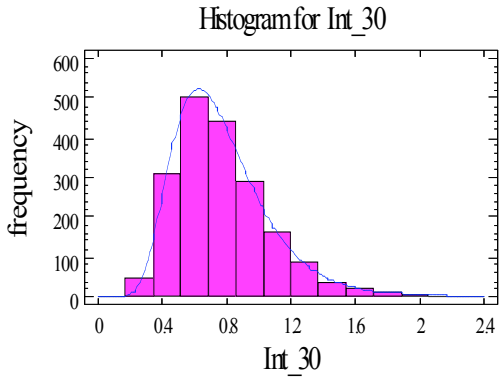
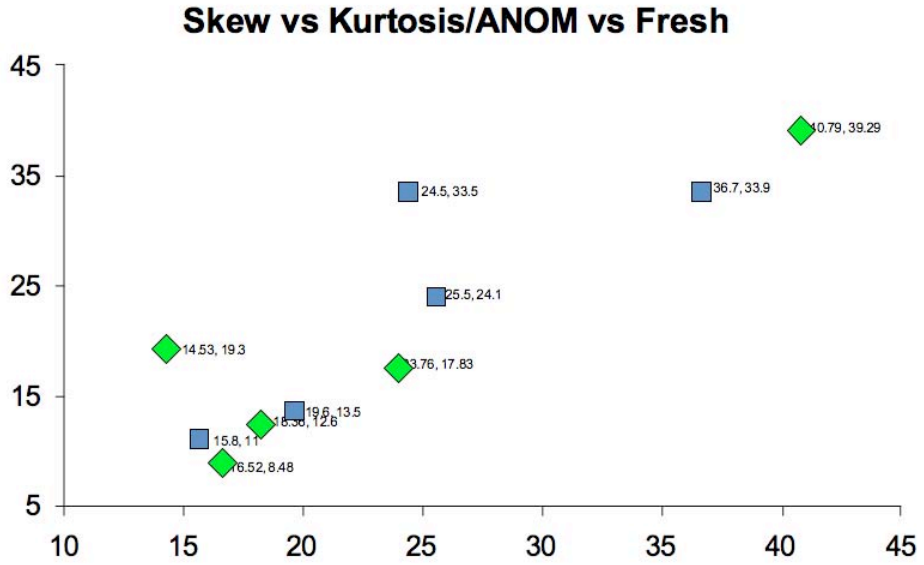
Statistical analysis of high CPR craters

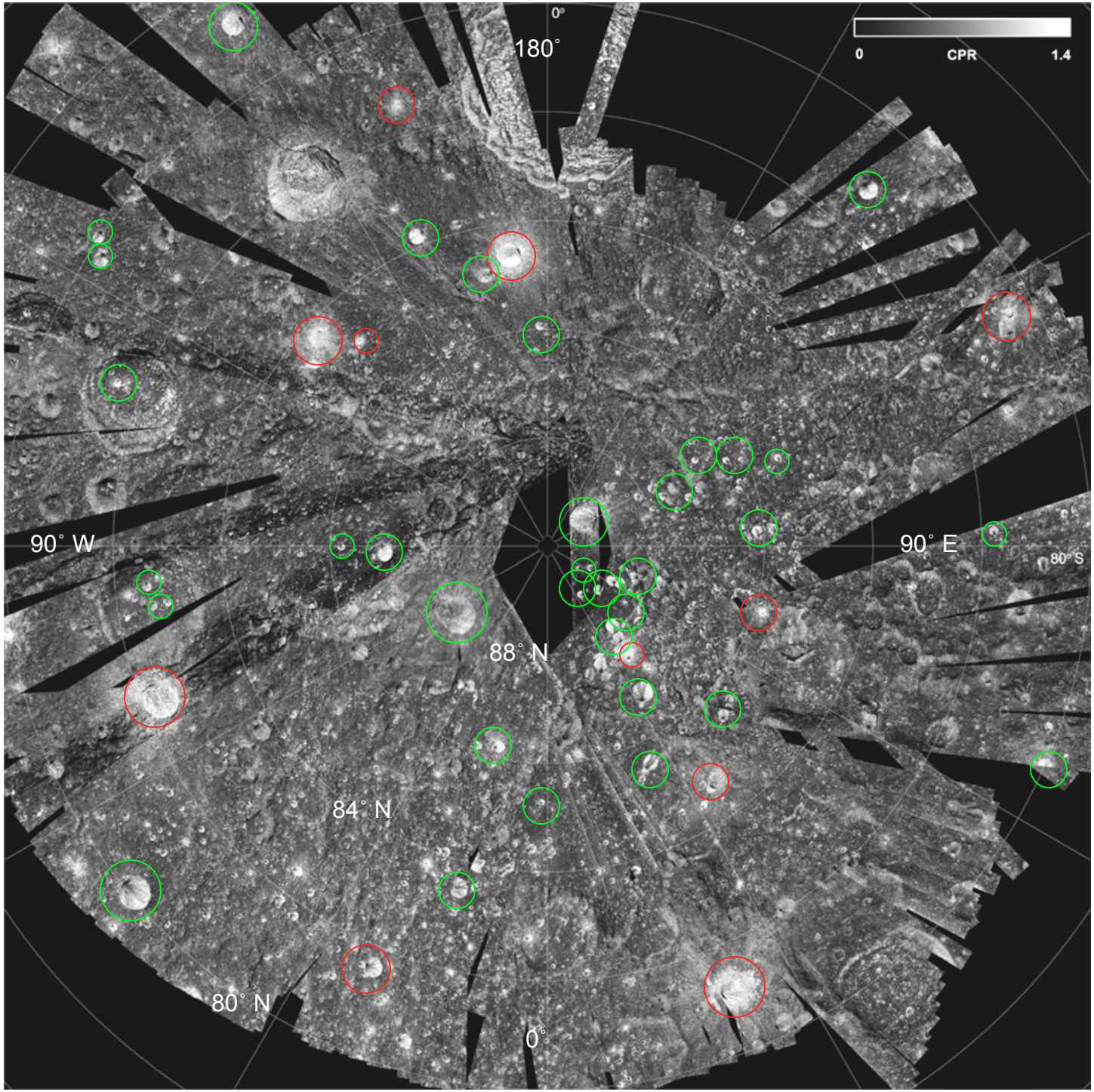
- Analyzing all polar craters, fresh and anomalous, to determine statistical properties of the high CPR
- All distributions are log-normal
- Initial analyses suggested to Spudis *et al.* (2010) that anomalous crater Rozhdestvensky N had CPR distribution distinct from “normal”crater Main L
- New analyses confirm and extend this result
- Additional work will include both poles, non-polar examples





Fresh craters

Anomalous craters



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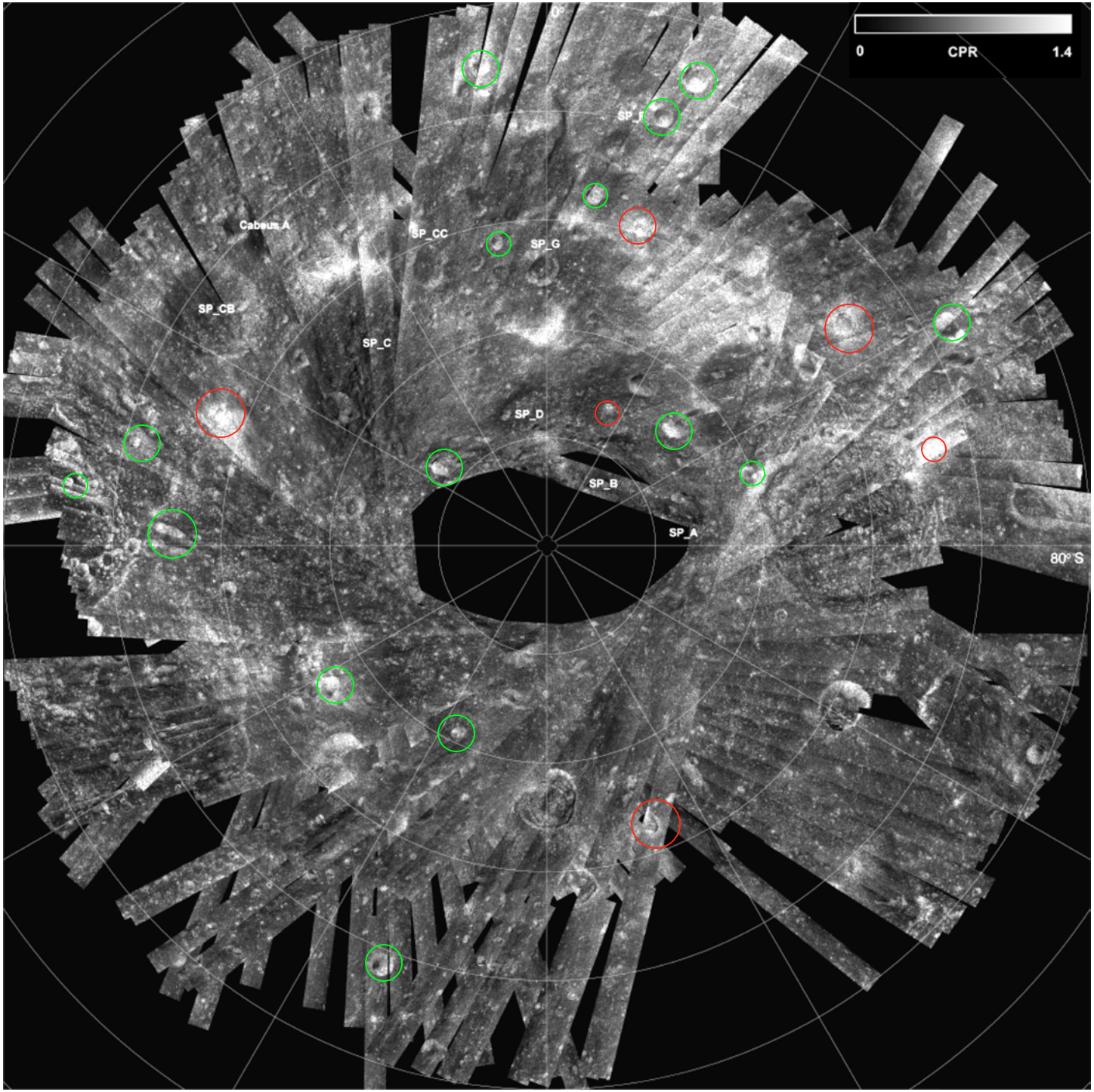
Fresh craters

Anomalous craters



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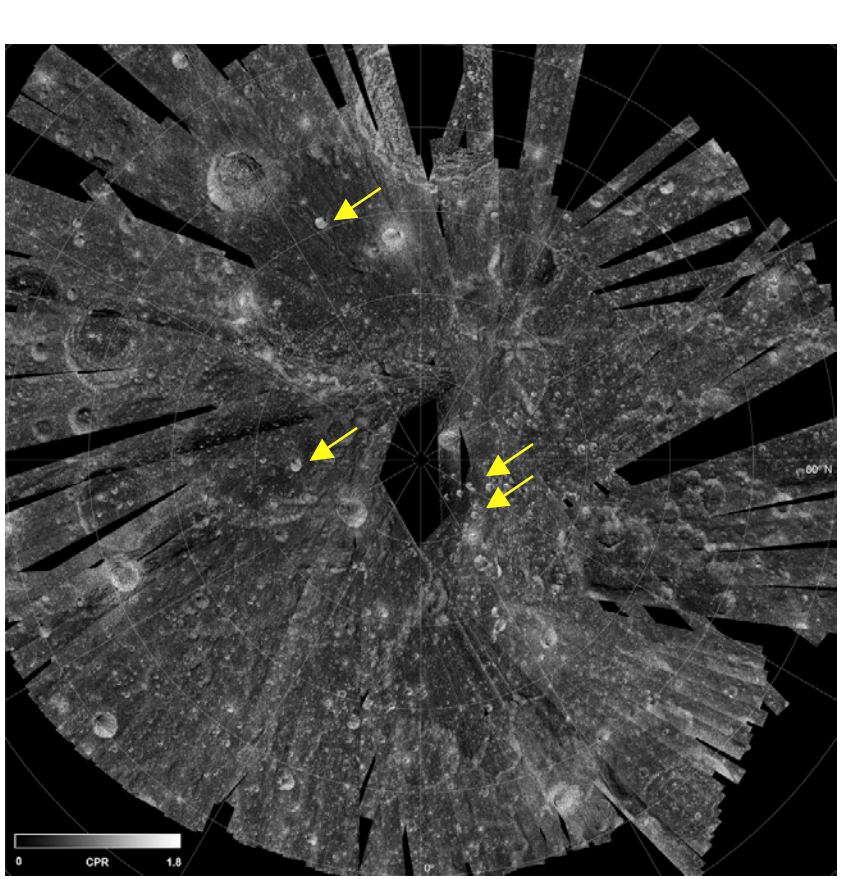
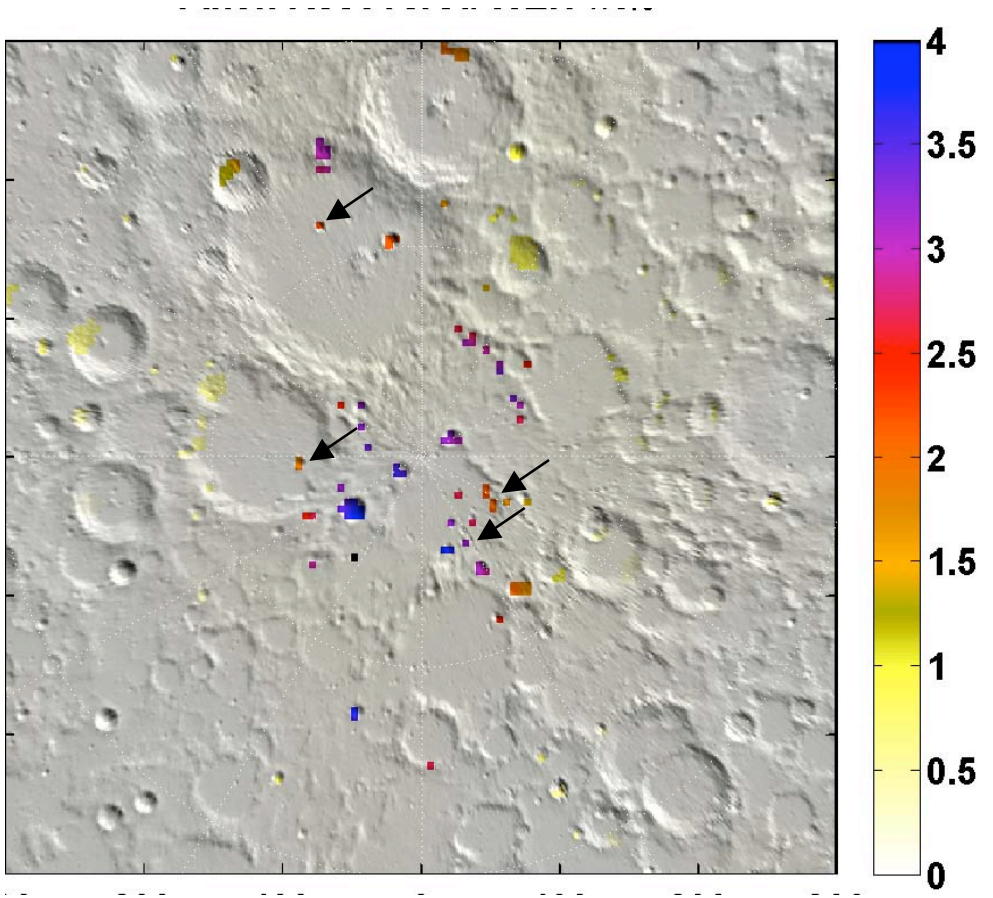
CPR v. Neutron data

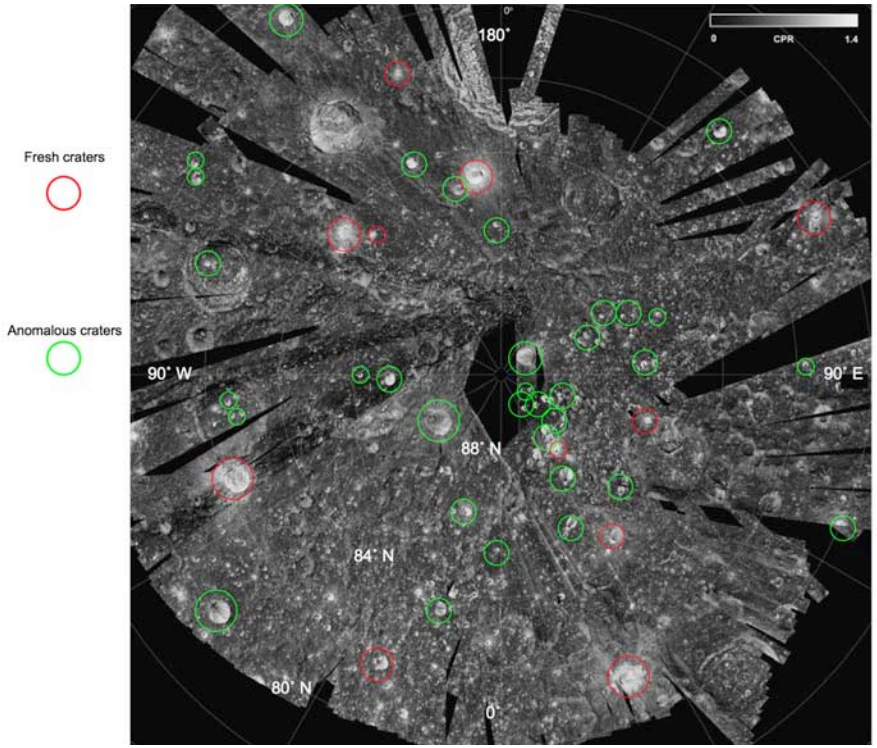


Mini-SAR CPR



LP Neutron Pixon Model

How Much Ice?



	D (km)	A (km^2)	V (m^3)/m (mT)
1			
2	12	113.04	24000000
3	8	50.24	16000000
4	7	38.465	14000000
5	5	19.625	10000000
6	6	28.26	12000000
7	8	50.24	16000000
8	3	7.065	6000000
9	5	19.625	10000000
10	4	12.56	8000000
11	4	12.56	8000000
12	8	50.24	16000000
13	21	346.185	42000000
14	18	254.34	36000000
15	7	38.465	14000000
16	12	113.04	24000000
17	3	7.065	6000000
18	8	50.24	16000000
19	6	28.26	12000000
20	11	94.985	22000000
21	6	28.26	12000000
22	4	12.56	8000000
23	5	19.625	10000000
24	4	12.56	8000000
25	6	28.26	12000000
26	4	12.56	8000000
27	3	7.065	6000000
28	3	7.065	6000000
29	8	50.24	16000000
30	17	226.865	34000000
31	4	12.56	8000000
32	34	907.46	68000000
33	4	12.56	8000000
34	6	28.26	12000000
35	5	19.625	10000000
36	4	12.56	8000000
37	4	12.56	8000000
38	3	7.065	6000000
39	8	50.24	16000000
40	5	19.625	10000000
41	11	94.985	22000000
42			
43	Total ice (m^3)		608000000
44			
45	Total reg (m^3)		5.652E+11
46			
47	Concentration		0.001075725

Observed high CPR area in shadowed craters x 10(λ) thickness
Total N. Polar ice ~ 6 x 10^8 m^3 = 600 million mT
Average fuel mass in Shuttle ET = 735 mT (735,000 kg)
Enough LH_2/LO_2 for one Shuttle launch equivalent *per day* for more than 2200 years

LUNAR AND PLANETARY INSTITUTE

The Lunar Hydrosphere

The Five Flavors of Lunar Water

Water is or was in the lunar interior (as a *minor* component; 250-700 ppm)

- Water from deep mantle (> 400 km depth) component of volatiles driving lunar pyroclastic eruptions

Water and OH molecules present at latitudes > 65° at both poles

- Present as adsorbed monolayer and/or bound in mineral structures
- Increasing concentration with increasing latitude (~800 ppm and *greater*)
- Temporally variable; preferentially located in cooler locales (it's moving)

Exospheric water is present in space above the south pole

- MIP mass spectrometer measured ~ 10^{-7} torr partial pressure H_2O

Water ice is admixed into regolith in polar regions

- LCROSS site (floor of Cabaeus) is 5-10 wt.% water; both ice particles and water vapor ejected during impact
- Other cometary volatiles are present (e.g., carbon dioxide, methane, sulfur dioxide, methanol, ethanol)
- Concentrations vary laterally, vertically; "fluffy" physical nature

Thick (~2 m), "pure" water ice is found in some permanently shadowed craters near the poles

- High CPR materials in over 40 craters (3-12 km dia.) near north pole
- Suggest over 600 million metric tonnes of "pure" water ice; reserves of ice mixed with dirt are much greater

Summary

Mini-SAR successfully mapped more than 90% of both polar areas

Thirteen non-polar areas analyzed; results consistent with previous S-band radar mapping from Earth

Areas of high CPR have been identified:

- Some high CPR is clearly associated with surface roughness (e.g., Main L ejecta blanket)
- Some deposits (e.g., near north pole on floor of Peary) show high CPR and are restricted to the *interior* of craters; these features are in permanent darkness.
- Statistical analysis suggests that these features constitute a distinct population from normal, fresh crater high-CPR features

Anomalous craters are found at both poles and correlate with Pixon model reconstructions of LP neutron data and areas of low surface temperature revealed by DIVINER

These anomalous deposits are probably water ice. Over 600 million m^3 are present in vicinity of north pole in this form

Mini-RF high resolution SAR of polar areas